Modeling and Total Maximum Daily Loads

One in a series of TMDL white papers from the Clean Water Network

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Total Maximum Daily Loads (TMDLs) are watershed cleanup plans for our most polluted waters. As such, TMDLs are of huge interest to the members of the Clean Water Network. Over the next decade or more, Network organizations and their members will be faced with reviewing approximately 40,000 cleanup plans. These plans will be key to progress on clean water. However, with so many plans and so many of them requiring technical review, watershed organizations may be quickly overwhelmed.

To help mitigate this problem, the Network is producing a series of "white papers" on technical and policy issues associated with TMDL cleanup plan development and implementation. These white papers are designed to help the dedicated layperson constructively weigh in on the TMDL process or on a draft TMDL cleanup plan that is out for public comment. For a more general introduction to TMDL review, see the Network's handbook: *The Ripple Effect*.[1]

This paper focuses on the use of models in TMDL development. Citizens involved in TMDL cleanup plans need to know when a model should be used and when it shouldn't, how complex (or how simple!) a model needs to be to be successful, what models are out there, and how they can best watchdog modeling efforts. For other papers in this series, visit our website at www.cwn.org or call 208-345-7776.

1. Introduction

Models describe complicated systems through a set of equations that help us understand and solve problems. In complex situations, computer spreadsheets or specialized computer programs are used. In the case of TMDLs, models can replicate the generation of pollutants and their movement across land and through rivers, lakes or coastal waters. Regulatory agencies rely on models to answer questions such as:

1. What are the current sources of pollution and what pollutant loads do they contribute?
2. What is the maximum pollutant load or cap, called the loading capacity, that the water body can receive while still meeting water quality standards?
3. What set of pollutant reductions should be assigned to each source to reduce pollutant loads in order to meet the cap?

When assessing the current sources of pollution (Question 1), models are used to identify point source dischargers and nonpoint source land areas that contribute to the problem. Models help quantify the pollutant contribution of each source to the impaired water body and help calculate the total existing load.

When setting the pollutant cap or loading capacity (Question 2), models may be used to determine the maximum amount of a pollutant that can reach the water body while still meeting water quality standards. To set the pollutant cap, models must take into account what happens to a pollutant once it reaches a waterbody—

its movements and transformations and interactions—and must be able to predict resulting pollutant concentration and compare them to the state water quality standard.

To determine a set of pollutant reductions necessary to meet the cap (Question 3), models help to account for the effects of reducing pollutant loads from a variety of sources, at potentially different levels. For example, modelers could test approaches such as equal reductions from all polluters, lowest cost reductions, or other approaches in order to find the best method for dividing up the total pollutant load.

Not only do models describe complex scientific processes, but they also serve as a database for storing and integrating large amounts of data that are sometimes necessary for developing a TMDL.

2. Deciding when a model is needed: the complexity question

Clearly models are very useful tools. However, not every TMDL will necessarily need to utilize a model. It sometimes seems like the answer to every TMDL question has become either "let's find a way to model that" or "I don't know where that came from, but the model says so." While models can and should be used in many situations, the first questions to ask yourself about models and TMDL cleanup plans are:

1. Do I need a model to understand what is going on here and to come up with a solution?
2. Do I have enough high quality data to support the use of a model?

The first question can be answered by balancing the pros and cons of using a model and the complexity of the situation in your watershed. Modeling can be time and resource intensive, data needs may be intense, specialized staff skills may be required, and assumptions in the model may not match the reality in the watershed. If the situation in your watershed is straightforward, the solution may be too. For example, at its most basic the TMDL's loading capacity is simply the water quality criteria (usually a concentration[2]) multiplied by a flow and a conversion factor to make the units match.

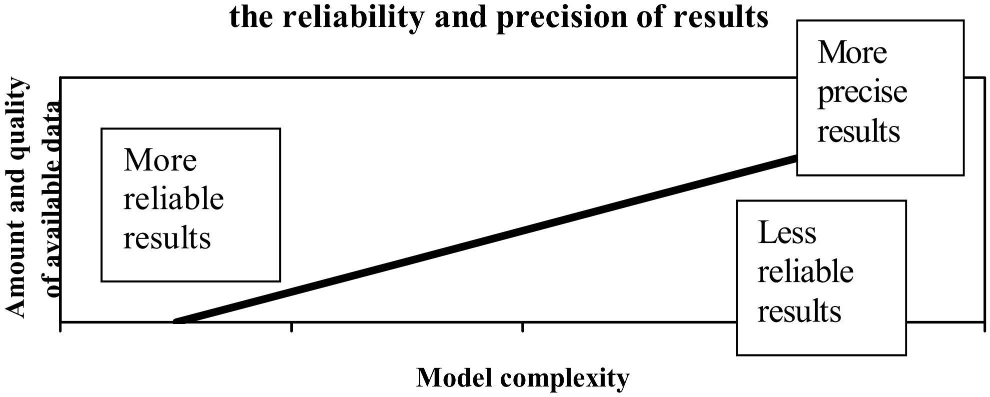
Loading capacity = Concentration X Flow X Conversion Factor

For more on this equation, see the Network's TMDL handbook – *The Ripple Effect: How to make waves in the turbulent world of watershed cleanup plans*. Try applying this simple approach first, especially if you have a numeric water quality standard.

For the second question about models and TMDL development – "Do I have enough high quality data to support the use of a model?" – there are many factors to consider. The answer to this question will depend not just on the amount and quality of monitoring data you have, but also on the nature of the pollutant, the nature of the problem, the level of precision needed, and other factors.

However, the basic concept to keep in mind is that the amount and quality of available data and the complexity of the model affect the reliability and precision of the results. Consider the following graph:[3]

The effect of available data and model complexity on the reliability and precision of results



This graph shows that the complexity of a model and the amount and quality of available data determine whether or not the modeling results are reliable and precise. The goal should be to develop as reliable and as precise a TMDL as possible, by properly matching the chosen model to the amount of data available, and by choosing as complex a model as is feasible.

In a perfect world, enough high quality data would be available to properly use a complex model. This situation would plot toward the upper right side of the graph, above the diagonal line; relatively reliable and precise results would be expected. In the real world, data may be scarce. If data are insufficient to use a particular model, the situation would plot below the diagonal line, and less reliable results would be expected. So, we can help mitigate a lack of data by choosing a less complex model.[4] Sometimes, simplified alternatives to modeling may be most appropriate as they will generate more precise and reliable results.

3. Alternatives to models for TMDL development

If funding, data, or time are not sufficient, or if scientific knowledge or the models themselves are not up to the task, all is not lost. Simplified alternatives to modeling may be most appropriate. While the simplified approaches described here can be used in combination with computer models, they can also be used independently when information or staff expertise will not support the use of a model.

We can help mitigate a lack of data by choosing a less complex model. Sometimes simplified alternatives to modeling may be most appropriate as they will generate more precise and reliable

Alternatives for assessing the sources of pollution (Question 1), especially for non-point source loads, include: monitoring source inputs directly, investigating aerial photographs to determine the location and scale of sources, reviewing literature values that assign discharge levels based on land use or other factors, reviewing permit files, reviewing county zoning and land use maps, and more.

When calculating pollutant caps (Question 2), simplified approaches include calculating the cap based on the equation presented in Section 2. But if a numeric water quality criterion does not apply, other possible approaches include setting caps based on loads in unimpaired reference water bodies or based on historical loads to the same water body from the time before the impairment started. Values (often called "literature values") that scientifically define a non-impaired level of water quality may also be available from textbooks, scientific research papers, or other sources.

Alternative options to modeling for assigning pollution load reductions (Question 3) include approaches such as equal reductions for all sources, equal (lowered) concentration limits for all sources, a lowest cost scenario, and more. Again, these approaches may feed into a complex model, but can also be used without models in relatively simple cases.

For examples of TMDLs developed with non-modeling approaches, see www.epa.gov/region09/water/tmdl. Look at Redwood Creek (uses sediment loads from reference watersheds to calculate the pollutant cap for the Redwood Creek basin), Noyo River (uses historical loads from before the river was impaired to set the pollutant cap), or Van Duzen River (uses trends of improvement for a set of sediment-related habitat values).[5]

The pros and cons of non-modeling approaches must be considered. For more on the approaches — and the pros and cons of the approaches — see the *Ripple Effect* handbook.

Pros of alternative approaches.
On the positive side, alternative methods can be easier to explain to the public and so may cause less fear. They may make TMDL development cheaper and faster to complete, especially if the data or research are already available. The alternatives do not require specific modeling expertise so may be achievable with existing agency staff. Alternatives may be the only reasonable methods available, given the limits of scientific understanding, modeling capabilities, or budgets.[6]

Cons of alternative approaches.
The cons of non-modeling approaches will vary by the alternative approach chosen. Historical data may not be extensive or may not account for natural changes in the watershed that have occurred over the years. Due to differences in hydrology, topography or other factors, reference stream conditions may not accurately define the goal for your stream if the reference is not carefully selected. Without a model, it may be tough to confirm that allocation scenarios will indeed result in meeting water quality standards, since test "runs" of different allocations cannot be produced like they can in models.[7]

More generally, alternative approaches are generally less complex, and therefore may not produce results as precise as those from complex computer models with large data sets (assuming however that such a data set exists – see the discussion in Section 2 of data quantity and quality, model complexity and the reliability and precision of results).

4. The range of complexity in TMDL models: the complexity question revisited

In Section 2 we discussed the relationship between available data, model complexity, and the reliability and precision of the results. The focus in that section was on whether or not to use a model. However if TMDL developers decide to use a model, the same tradeoffs apply when choosing how complex the model should be. This section considers various levels of complexity of loading models and receiving water models. This section also briefly discusses integrated models, which unify loading and receiving water models. Section 6 provides an overview of commonly used models.

4.1. Loading models

Loading models are used to answer the first question from Section 1: What are the current nonpoint sources of pollution and what pollutant loads do they contribute? These models range from the very simple—where loading is calculated as a function of land use type—to the more complex, where the model calculates loadings based on the effects of rainfall, transport, runoff processes, and more.[8]

Loading models can be divided into three levels of complexity: simple, mid-range, and complex.

Simple loading models are usually used when agencies are faced with data, budget, or time constraints. That doesn't mean the simple models are necessarily bad. They are still useful for judging the relative significance of different sources, focusing monitoring efforts, or creating a TMDL cleanup plan for simple problems. They may also be the only modeling approach that can be used to produce reliable results, given a scarcity of data (see Section 2). Downsides of simple models include the fact that they may lose resolution, they may look at large time scales and overlook individual or seasonal pollution events, they may rely on default values, and they may provide only rough estimates of loadings.

Mid-range loading models add another layer of complexity. They can be used to estimate pollutant contributions from multiple land uses and from individual areas. Mid-range models can address seasonal or storm event pollution loads in addition to the annual or inter-annual timeframes addressed by simple models.[9] They can also evaluate sources over broad geographic areas, and many can be integrated with geographical information systems

Loading models are used to answer the first question from section 1:

What are the current nonpoint sources of pollution and what pollutant loads do they contribute?

(GIS) to provide visual output such as maps.

One downside of mid-range models is that they still rely on simplifications and large time steps, which can limit their precision to within about an order of magnitude and may restrict their power to compare situations.[10]

Complex loading models provide the best representation of how pollutant loadings are generated and transported to receiving water bodies. Detailed models can help identify the causes of problems rather than just the condition in the watershed. These models address shorter timeframes – using daily or hourly time steps– so may be best poised to produce a true daily load analysis. However, detailed models require considerable time, expense, and skill to use, and considerable data to produce reliable results.

AGNPS is an example of a loading model. (See Section 6 for information on t his model.)

….steady-state models use constant inputs that do not vary over time.

….dynamic models allow inputs to vary day-by-day or hour-by-hour and may consider complex reactions among differ-

4.2. Receiving water models

Receiving water models help to answer the second and third questions from section 1:

2. What is the pollutant cap that the water body can receive while still meeting water quality standards?
3. What set of pollutant reductions should be assigned to each source to reduce pollutant loads to meet the cap?

To answer these questions, these models predict the response of the receiving water body to a set of pollutant loadings, by simulating the processes that occur within water bodies. For example, these models can predict the effects of hydrodynamic factors, such as flow, and temporal factors, such as the time it takes for certain pollutants to break down in the system. Receiving models also account for the location of the pollutant sources and for non-conservative pollutants (i.e., those that degrade or transform).

To understand receiving water models, you need to understand the concept of mass balance. A mass balance equation compares the mass of a pollutant that enters a defined area with the mass leaving the area. But keep in mind that there are often several ways for a pollutant to enter or exit an area. For example, chemical reactions may transform a pollutant into something else, or a pollutant may adsorb to sediment and settle out of the water column. Mass balance equations must therefore account for not just the initial input of a pollutant to a water segment and the transport of the pollutant through the segment, but also reactions and changes in storage within the segment.

The complexity of a receiving water model depends on how it incorporates pollutant inputs, reactions, and transport into the model. For example, the simplest steady-state models use constant inputs that do not vary over time. More complex dynamic models allow inputs to vary day-by-day or hour-by-hour and may consider complex reactions among different pollutants.

When sufficient data, budget, and time are available, more complex receiving water models will result in more reliable and more precise results. But similar trade-offs apply to receiving water models as to loading models: simple models may be most appropriate in some situations and, given a scarcity of data, may provide the most reliable results.

Examples of receiving water models include QUAL2E and WASP6. (See Section 6 for information on these models.)

4.3 Integrated models

Integrated models link loading models with receiving water models into a unified system, and often link these models with one or more databases or GIS. These models may link together a set of specialized models and allow the user to choose the most appropriate models for the particular problem at hand.

Integrated models are typically complex; examples include BASINS and WARMF. (See Section 6 for information on these models.)

Integrated models link loading models with receiving water models into a unified system, and often link these models with one or more databases or a geographic information system.

5. Calibrating and verifying models

Calibration and verification should be used to gain confidence that the model is a reasonably accurate representation of reality.

Calibration involves fine-tuning the model by tweaking input data in appropriate ways so that the model results better predict reality. This process involves entering data into the model, running the model, comparing the model results to actual monitoring data to see how well they mimic reality, and adjusting certain appropriate input data until the model results reasonably match the monitoring data.

For example, with an integrated watershed-scale loading and receiving water model, a modeler would enter information into the model that describes, among other things, land use, point source dischargers, rainfall and soil characteristics. The model would calculate flow and instream water quality concentrations for every day of the simulation period at many locations along each simulated water body. The modeler would then compare the calculated flows and concentrations with actual, real-world measurements collected at the same time and place that the model is being run for. Based on this comparison, the modeler would adjust certain input data (such as soil characteristics) that affect instream flows and pollutant concentrations, and would re-run the model to see if the results better match actual values. This process would typically take several iterations before an acceptable calibration was found.

Verification involves splitting data into two sets. The modeler would create a calibrated model using one set of data. Then, the data that was set aside would be entered into the calibrated model, and the model would be run again to see how well the calibrated model predicts instream flows and concentrations using this second

Calibration involves fine-tuning the model by tweaking input data in appropriate ways so that the model results better predict reality.

set of data.

Models can be calibrated and verified using historical data or recent data. It's more important to have enough of the right kind of data over a particular time period; it's less important whether this time period occurred a decade ago or just last year. However, if substantial changes have occurred in the watershed over the past decade, using old data to calibrate the model would cause problems. On the other hand, calibrating and verifying a model with existing historical data can save time and money, since no new monitoring is required.

6. Models used in TMDL development

There are far too many models in use to do justice to them here! However, we can highlight a few specific models that have been used to develop TMDLs. Please note that some states are developing their own models based these models. See Sections 7 and 8 for more information on digging in deeper on the model your state agency is using and for resources with more information on a wider range of models.

AGNPS. The Agricultural Nonpoint Source Pollution (AGNPS) model is a watershed-scale loading model. It is designed to evaluate nonpoint source pollution contributions from agriculture by comparing the pollution impacts of different conservation practices.
<u>To be used for:</u> Pollutants: sediment, nutrients, pesticides, and chemical oxygen demand.[11] Situations: erosion, nutrient runoff, and chemical transport.
<u>Strengths:</u> Includes source accounting so pollutants can be tracked as they move through the watershed. Can model single, multiple, or diffuse sources as well as continuous or intermittent discharges. Can be linked to GIS software so it can present data in visual form.
<u>Weaknesses</u>: Is designed for agricultural watersheds only. Does not simulate subsurface soil processes so it only models above-ground processes like erosion on farmland, and doesn't track the water once it goes underground. Does not account for nutrient transformation and in-stream processes. Does not address urban runoff issues.
<u>For more information</u>**:** Visit www.wcc.nrcs.usda.gov/water/quality/wst.html for more information on the AGNPS model, including a downloadable version and training materials.

BASINS. Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) is an integrated model that includes both receiving water and watershed-scale loading models. It is a collection of existing models, packaged together with a graphical GIS-based user interface.
<u>Best used for:</u> Modeling nutrients, sediment, bacteria and toxics.
<u>Strengths</u>: Addresses both point and nonpoint source loadings. Includes the Nonpoint Source Model, which is a Windows interface of HSPF (described below), TOXI-ROUTE, and QUAL2E. Linked to GIS software so it can present data in visual form.
<u>Weaknesses</u>: TOXI-ROUTE uses simple dilution calculations so may not be appropriate for complicated situations. QUAL2E can be substituted in these cases.

For more information: This model is free from U.S. EPA. Find the model, data, and support information at www.epa.gov/ost/basins/.

HSPF. The Hydrological Simulation Program – FORTRAN (HSPF) model is a watershed-scale integrated model that allows you to calculate surface runoff and subsurface discharge of pollutants. It also models receiving water quality. HSPF is a dynamic model and has been applied extensively.
Best used for: Well mixed streams, rivers, lakes and reservoirs. Pollutants: nitrogen, phosphorus, pesticides, organics, and BOD-DO interactions.[12]
Strengths: Allows modeling of both pollutant load and water quality (concentration) in complex situations. Can model single, multiple, or diffuse sources as well as continuous or intermittent discharges. Allows for evaluation of best management practices and design criteria.
Weaknesses: Should only be used for well-mixed rivers and reservoirs. Requires a lot of data in order to run, calibrate and verify the model. Extensive water quality data is needed in order to calibrate and verify the model. Highly trained modelers are required.
For more information: Visit www.epa.gov/OWOW/watershed/tools/model.html#12 or water.usgs.gov/software/hspf.html.

QUAL2E. The Enhanced Stream Water Quality Model (QUAL2E) is a receiving water model that can simulate multiple parameters in a branching stream system.[13]
Used for: Streams, rivers, lakes, reservoirs, and estuaries. Pollutants: dissolved oxygen, BOD, temperature, chlorophyll a, ammonia, nitrite, nitrate, organic N, organic and dissolved phosphorus, coliforms, and more.[14]
Strengths: Has been in use for over two decades for wasteload allocation studies and other management activities.
Weaknesses: This is a complicated model that can be cumbersome due to the need for extensive field data and many adjustments. The steady state version of QUAL2E assumes DO values do not vary over the day/night cycle so does not reflect instream reality. The dynamic version of the model is designed to account for diurnal DO swings, but is very complicated to set up and verify.
For more information: Download from EPA at www.epa.gov/OST/QUAL2E_WINDOWS/.

WARMF. Watershed Analysis Risk Management Framework (WARMF) is an integrated model that predicts changes in water quality due to point and nonpoint source control, land use changes, and best management practices.
Used for: DO, bacteria, pesticides, algae, total P, total N, TOC, TSS, acid mine drainage pollutants.
Strengths: Data entry and results are based on a GIS-based graphical user interface. Includes a module designed specifically for TMDL development, and a consensus module for facilitating stakeholder processes.
Weaknesses: A relatively new model, it has only been used for a few TMDLs.
For more information: www.systechengineerng.com/warmf.htm.

WASP6. Water Quality Analysis Simulation Program (WASP6) is a receiving water model that is used to assess the fate and transport of both conventional and toxic pollutants. It predicts concentrations of water quality parameters over time.

Used for: River, streams, lakes, reservoirs, estuaries, and coastal waters. The prediction of the fate and transport of organic chemicals (PCB, PAH, TCE, Dioxin), and metals (simple speciation).
Strengths: It has a track record of use for regulatory purposes. Model processes incorporate temperature, salinity, bacteria, DO-BOD, the nitrogen and phosphorus cycles, phytoplankton, and more.
Weaknesses: Does not handle mixing zones or near field affects. Does not handle sinkable/floatable materials.[15]
For more information: For general information and a download of the new WASP update, visit: www.epa.gov/region4/water/tmdl/tools/wasp.htm. Trainings are available from EPA by contacting Tim Wool at wool.tim@epa.gov.

7. Action Items for TMDL activists faced with a model

Models are technical and data-rich so the questions could be endless. At the very least, if the TMDL uses a model, ask the following questions:

- What model did/will the agency use and why did they choose it?
- Did the agency consider any simplified approaches that could avoid the need for modeling?
- Look up the model in this paper or in EPA's *Compendium of Tools for Watershed Assessment and TMDL Development* (see Section 8 for information on where to find this document). Is the model chosen appropriate for the pollutant of concern? For the scale of the watershed under review? For the amount of data available?
- Is the level of complexity appropriate for the problem it addresses? For the quantity and quality of the available data?
- What data sources were used? Did the agency include outside data such as that from university researchers, point source dischargers, or citizen watershed groups?
- If it is a dynamic model, does the agency use both wet and dry years in the time period being simulated?
- If it is a steady state model, does the agency identify the critical flow for the problem (this will generally be a low flow situation for point source dominated problems and a high flow situation for nonpoint source dominated problems)? In addition to flow, does the model account for other possible critical conditions such as temperature, season, time of day, discharge levels, etc.?

- Has the model been calibrated and verified with real data? How?

- What are the assumptions behind the model? Does that match your understanding of the watershed? Some assumptions are useful tools, but you'll need to examine the assumptions and decide if they are appropriate. Models may incorporate assumptions about issues such as:
    - Point source discharges may be assumed to be constant over time, while in reality they may vary substantially from day to day or from hour to hour.
    - The pollutant cap calculated by the model may not be a true maximum daily load, but instead may be an average load.
    - The model may not account for atmospheric deposition of pollutants, which may affect the TMDL.
    - Generic data may be entered because local data are unavailable, but this generic data may not accurately describe local conditions.
    - The model may use estimated or calculated data for flow remember, flow is half of the basic equation for setting your loading capacity!

- Models may include assumptions about upstream influences on pollution concentrations. Are there local conditions that the model didn't evaluate or that the modelers may not be aware of?

- If the data collection and modeling process uncovered NPDES dischargers with permit violations, were appropriate enforcement actions triggered?

These questions should get you started, but you'll likely turn up more questions as a result. If you are skeptical about any of your agencies answers, it might be time to consult an expert. Try your local colleges and universities for support. Alternatively, contact the Clean Water Network at 208-345-7776 for referral to experts.

8. Resources for more information

- U.S. EPA, Office of Water, *Compendium of Tools for Watershed Assessment and TMDL Development*, May 1997. (EPA841-B-97-006) This document profiles many more models then the ones described in this paper. Order it online at www.epa.gov/ncepihom/index.htm.

- If you need advice to help understand and assess a model or a TMDL, contact the Clean Water Network at mkfrey@mindspring.com or 208-345-7776. Network staff can connect you with experts and resources.

- The TMDL.org site has model information at www.tmdl.org/software.html. This site offers information on BASINS, other models, and the

Utah Water Research Laboratory at Utah State University's "TMDL toolkit."

- EPA's main modeling page is at www.epa.gov/epahome/models.htm. This is an impressive compilation of links to many of the agency's modeling divisions as well as links to dozens of descriptions of individual models and, in some cases, download sites for those models.

- EPA's Center for Exposure Assessment Modeling home page is at www.epa.gov/ceampubl/. This is a very technical site packed with information on many models. Not for the faint of heart, but includes information that may be useful for those dealing with toxic pollutants or other problems involving exposure issues.

- If you want to dig in deeper on modeling, lay hands on *Surface Water-Quality Modeling* by Steven Chapra (McGraw-Hill, 1997). This is good text on water quality modeling which describes equations recommended for various pollutants.

Endnotes

1. *The Ripple Effect* is available at www.cwn.org or by calling 208-345-7776.

2. Water quality criteria are usually expressed as mass/volume concentration measurements such as mg/L. The concentration measures the strength of the pollutant/water mix. For more on the relationship between concentrations and loads, see the Network's TMDL handbook – *The Ripple Effect: How to make waves in the turbulent world of watershed cleanup plans*.

3. This graph is based on one presented by Paul Freedman of Limno-Tech, Inc. in *Overview of Simplified Methods for Modeling in the TMDL Process.* Presented at the Water Environment Federation's TMDL Science Issues Conference, St. Louis, March 2001.

4. TMDLs developed with less complex models or simple alternatives to models may include additional monitoring requirements, a larger margin of safety to account for uncertainty, and built in revision procedures to take new data into account.

5. Smith, David, EPA Region 9. Non-modeling Approaches for Developing Sediment TMDLs. Presented at TMDL Science Issues Conference, St. Louis, March 2001.

6. Smith, David, EPA Region 9. Non-modeling Approaches for Developing Sediment TMDLs. Presented at TMDL Science Issues Conference, St. Louis, March 2001. Freedman, Paul. Limno-Tech, Inc. *Overview of Simplified Methods for Modeling in the TMDL Process.* Presented at the Water Environment Federation's TMDL Science Issues Conference, St. Louis, March 2001.

7. Ibid.

8. U.S. EPA, Office of Water, *Compendium of Tools for Watershed Assessment and TMDL Development*, May 1997 (EPA841-B-97-006).

9. Ibid.

10. Ibid.

11. Ibid.

12. TMDL.org's *Comparison of Water Quality Models – Dynamic and Steady State*. Available at: http://www.tmdl.org/MODELCMP.pdf.

13. U.S. EPA, Office of Water, *Compendium of Tools for Watershed Assessment and TMDL Development*, May 1997 (EPA841-B-97-006).

14. TMDL.org's "Comparison of Water Quality Models – Dynamic and Steady State. Available at: http://www.tmdl.org/MODELCMP.pdf.

15. Wool, Tim. *Re: WASP5*. Email communication with Merritt Frey. March 2002.